Turbulence Simulation of Laboratory Wind-Wave Interaction in High Winds and Upscaling to Ocean Conditions

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LONG-TERM GOALS

Wind-wave interactions are of fundamental importance as they determine the sea surface drag and scalar exchange between the atmosphere and ocean. This is particularly important at high winds since air-sea coupling controls tropical cyclone (hurricane) formation and intensity. There is large uncertainty in the bulk momentum and heat surface exchange coefficients (C_d, C_k) derived from field observations and laboratory experiments for varying wind speed, wave age, swell amplitude and direction, and in the presence of spray, with an even greater debate as to the underlying dynamical processes that couple the winds and waves[1,2,3,4,5]. In this context, the overarching theme of this project is to identify the physical processes that couple winds in the marine atmospheric boundary layer and the underlying surface gravity wave field at high wind speeds.

OBJECTIVES

Essentially, the proposed project seeks to reconcile laboratory and field measurements of wind-wave interaction and surface drag in high to extreme winds using turbulence resolving large-eddy simulation (LES). The basic science question we address is: how confidently can we upscale dynamical processes and measured statistics in small-scale laboratory experiments to full-scale high wind ocean conditions?

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APPROACH

We build substantially on our accumulated expertise in sea surface processes and air-sea interaction. For this project, LES of the airflow over steep and breaking waves is carried out over a range of wind speeds and wave conditions matching selected laboratory wind-wave experiments. Simulation data volumes will be analyzed extensively to generate flow visualization, bulk mean flow and turbulence statistics and surface drag, and will be compared with the experimental results. This detailed intercomparison of simulation and experimental results will identify the fundamental dynamical processes in wind-wave interaction, viz., flow separation and reattachment, impacts of surface roughness and swell steepness as a function of non-breaking and breaking conditions. The second stage of the project will attempt to upscale the laboratory dynamical processes to full-scale oceanic conditions under high wind and hurricane forcing using LES of the full marine ABL.

The turbulence simulation method uses a novel approach that allows coupling turbulent winds to an underlying three-dimensional time-dependent wave field. In the simulations, the surface wave fields, which contain the essential breaking dynamics, are externally prescribed, i.e., measured space-time properties of the wave fields are imposed as a lower boundary condition in the computations. The LES code is highly parallelized and all computations are performed on massively parallel supercomputers.

WORK COMPLETED

Our effort during FY12 (first year of the project) has concentrated on how closely the LES modeling framework developed by Sullivan et al.[5] can replicate the findings reported in the laboratory investigation of Banner[6], which studied the marginal effect of breaking on the airflow over propagating wind waves. In summary, that investigation isolated and quantified breaking-induced separated air flow effects through detailed pressure and velocity measurements of the aerodynamic wave form drag and total drag, comparing breaking wind waves and comparably steep unbroken wind waves. It was found that the local waveform drag nearly *doubled* over the breaking waves - a very strong effect. Further, the average waveform drag contributed about 70-75% of the total wind stress on the water surface for both unbroken and breaking wave cases, and these total wind stress levels also nearly *doubled* when the waves were breaking.

Initial representative wave elevation distributions were estimated by digitizing the images in Figure 8 in Banner[6]. Initial estimates were made of the fluid surface speed distribution along these profiles by assuming a suitably-scaled cosinusoidal distribution for the steep unbroken wave, with a similar distribution for the breaking wave but with a compact downslope velocity distribution starting at the crest and finishing at the leading edge of the spilling breaker. A superimposed modulated wind drift was also incorporated in both cases.

The LES computations were carried out in domains of size $(X_L, Y_L, Z_L)/\lambda = (3, 1.5, 1)$, where the wavelength λ was 0.233m for the incipient breaking case and 0.235 m for the active breaking case. Each simulation was driven by a constant large-scale pressure gradient $(dp/dx)/\rho = 0.188$ m/s^2. Note that the range of wind speeds between the two cases is different because of the higher drag in the active breaking case. The discretization in the computations is $(N_x, N_y, N_z) = (256, 128, 128)$ grid points with uniform spacing in the (x-y) directions and a smoothly varying stretched grid in the vertical. In the terrain-following grid, the first grid point of the surface is located at approximately z = 0.001 m. The LES is carried out at high Reynolds number and assumes a smooth water surface with initial surface roughness $z_0 = 5x10^{-6}$ m. Both calculations were run until a statistically steady state is reached, approximately 30 large-scale eddy turnover times.

RESULTS

Snapshots of the horizontal wind field in an x-z plane for a case with incipient breaking (upper panel) and active breaking (lower panel) are shown in Figure 1. It is evident that the flow remains attached to the wavy surface in the upper panel, while there is significant flow separation at the surface in the lower panel. Hence the LES captures the strong difference that the breaking imparts, just as observed by Banner[6]. We are now at the stage of verifying the total aerodynamic drag and the form drag predicted by the model, and our initial estimates suggest that the drag for the incipient breaking case is too low. We are investigating model sensitivity to the surface velocity and initial roughness length.

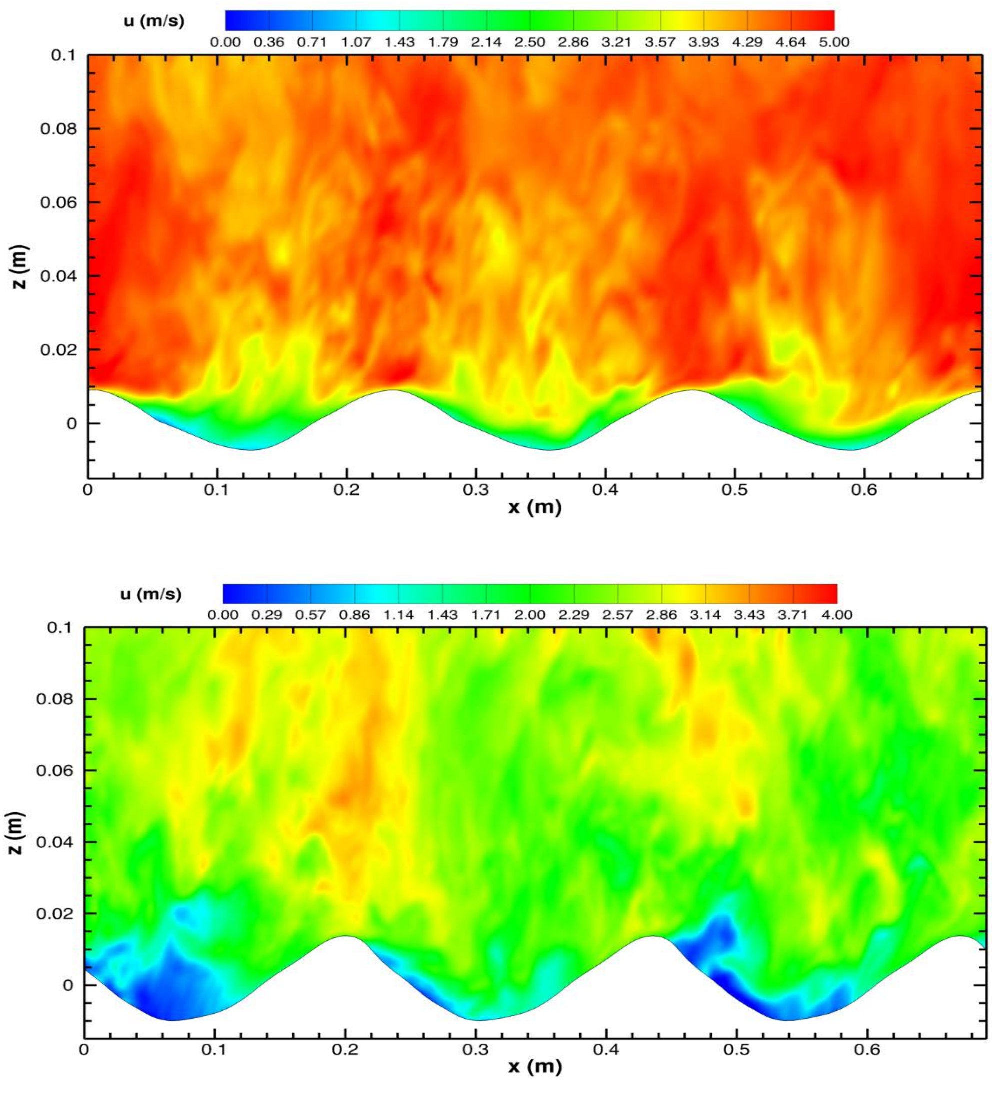

Figure 1: Snapshots of the horizontal wind field in an x-z plane for a case with incipient breaking (upper panel) and active breaking (lower panel). Note the consistent separated flow regions (blue) along the surface for the actively breaking case (lower panel), which is absent in the incipient breaking case. This has a very strong effect on phase-shifting the surface pressure field the wind, amplifying the form drag and total drag on the water surface.

IMPACT/APPLICATIONS

This study is aimed at advancing fundamental understanding of air-sea interactions, which play a critical role in forecasting marine weather, ocean waves and upper ocean dynamics. Central to air-sea interaction mechanics is the coupling between turbulence in the surface layers of the marine boundary layers and the connecting surface gravity wave field, which determines the sea surface drag and the scalar exchange between the atmosphere and ocean. The major impact of this effort will be a refinement of present knowledge of the influence of wave breaking and complex sea surface topography in air-sea interactions. This includes a reduction in the present large uncertainty in measured values of the momentum and scalar exchange coefficients for wind speeds greater than 20 m/s by clarifying their dependence on numerous physical factors, such as wind speed, wave age, wind-wave direction, wave spectral content, flow separation and surface roughness.

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